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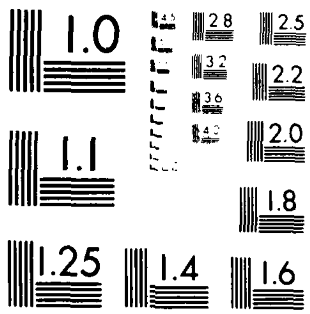

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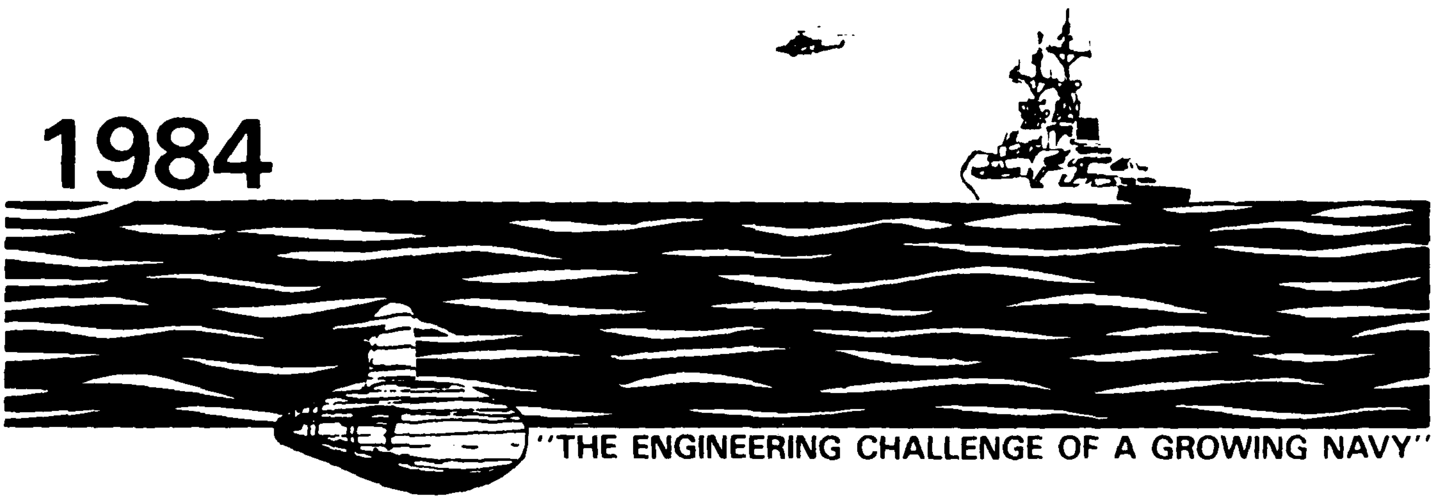

"THE ENGINEERING CHALLENGE OF A GROWING NAVY"

RETROFITTING OF BULBOUS BOWS ON U.S. NAVY AUXILIARY AND AMPHIBIOUS ~~WARSHIPS~~ WARFARE SHIPS FOR FUEL SAVINGS

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Retrofitting of Bulbous Bows on U.S. Navy Auxiliary
and Amphibious Warfare Ships for Fuel Savings

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The view expre3sed herein are the personal opinions
of the authors and are not necessarily the official
views of the Department of Defense or of
the Department of the Navy

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NOTATION

A_{BL}	Area of Projection of bulb on ship's centerline plane
A_{BT}	Transverse cross-sectional area of bulb at forward perpendicular
A_{MS}	Midship section area of ship to design waterline
B_B	Maximum breadth of bulb area
B_X	Maximum breadth of ship
B_{MS}	Breadth of ship at midship, at design waterline
C_{ABL}	Bulb lateral parameter
C_{ABT}	Bulb cross-section parameter
C_B	Block coefficient
C_{BB}	Bulb breadth parameter
C_{LPR}	Bulb length parameter
C_P	Prismatic coefficient
C_{VPR}	Bulb volumetric parameter
C_X	Maximum sectional area coefficient
C_{ZB}	Bulb depth parameter
L_{PP}	Length between perpendiculars
L_{PR}	Protruding length of bulb
V_{PR}	Volume of protruding bulb
V_{WL}	Displaced volume at design waterline
Z_B	Height of foremost point of the bulb

ABSTRACT

To meet energy conservation goals of the Navy, its attention has been focused on ways to reduce individual ship total resistance and powering requirements. One possible method of improving ship powering characteristics is by modifying existing individual ship hulls with the addition of bulbous bows. This paper will identify the merits of retrofitting bow bulbs on selected U.S. Navy auxiliary and amphibious warfare ships. A procedure for performing a cost/benefit analysis will be shown for candidate ship classes. An example of this technique for an amphibious warfare ship will also be provided. A brief discussion of future methods to be used for bulbous bow design such as application of systematic model test data and numerical hydrodynamic techniques will be given.

INTRODUCTION

Since its inception, the Navy's energy conservation program has been searching for ways to reduce the energy requirements of the fleet. One such area of fuel savings is in improving the hydrodynamic performance of ship hulls by reducing total ship resistance and powering requirements. Some of the energy conservation programs which reduce ship resistance are:

- Comprehensive hull cleaning and preservation program
- Propeller hub cap modifications
- Bearing-in-Rudder-Post shafting systems
- Improved/refined appendage designs

However, one way to reduce total ship resistance that has not been fully exploited for its potential is reducing wave-making resistance by retrofitting of bulbous bows on selected existing navy ships.

For some time naval architects have known that a bulbous bow can reduce a ship's wave-making resistance (Reference 1). In fact recent ship designs have utilized this potential way to reduce resistance by incorporating a bulbous bow into the hull form . However for those existing ships that were not originally designed with a bulbous bow the possibility of a bulbous bow retrofit still remains. Bulbous bows previously have not been retrofitted onto ships as the costs of fabrication and installation of the bulb far outweighed any potential fuel savings that could be achieved. Due to the tremendous increase in fuel costs since the early 1970's, this situation has now changed. Designed properly a bulbous bow can, for most auxiliary and amphibious warfare ships, now be expected to pay back its projected capital costs in 1/4 to 1/3 of the ship's remaining life time.

Procedures are now available which allow the naval architect to select bulb parameters without the extensive and time-consuming model test program that would normally be required. Once a bulb is designed a model test program coupled with this procedure would then be used only in an effort to verify the empirically based predictions. If other ship impact issues in addition to hydrodynamic concerns are satisfactorily resolved and the bulb shows potential for significant fuel savings during the remaining lifetime of the ship, a retrofit should receive serious consideration.

SELECTION OF CANDIDATE SHIPS

Several factors must be considered before one can determine the feasibility of retrofitting bulbous bows on ships. For the U.S. Navy the ship types which are considered most likely to realize a savings in fuel are certain auxiliary and amphibious warfare ships. This is because their hull form shapes and speed-length ratios are in the ideal range where bulbous bows have the maximum potential to reduce wave-making resistance. Their hulls also do not have bow sonar domes which would preclude bulb installation. Furthermore, the experience of commercial shipping with bulbous bows can be directly applied due to the similiarity of auxiliary and amphibious warfare ship hulls to merchant hull forms.

Now that it has been determined which ship types may benefit from a retrofit bulb, it becomes necessary to address the practicality of a bulb installation on each ship class. Concerns such as physical interference between a bulb and other objects such as ships anchors or bow thrusters must be examined. Review of the anchor arrangements of a ship might place constraints on the overall dimensions of the bulb while the cost required to fair the bulb plating into existing plating at the thruster tunnel openings might require the removal of these ships from consideration. Mission requirements must also be addressed; for example the requirement for LSTs to beach themselves and the infrequent time-at-sea underway of tenders would preclude either of these type ships from consideration.

All existing Navy auxiliary and amphibious warfare ship classes were examined to determine which classes should have a detail cost-benefit analysis done. The existing ship classes were placed in one of three categories: candidate, marginal, or non-candidate ships, on the basis of four criteria. These criteria as shown by Table 1 were the following:

TABLE 1.

Bulb Retrofit Criteria for
Auxiliary and Amphibious Warfare Ships

No.	Criterion	Issue	Favorable Response for Bulb Retrofit
1.	Speed	Does the vessel spend a major portion of its time underway at speeds corresponding to speed-length ratios ($V_k/\sqrt{L}$) between 0.8 and 1.9 where a bulbous bow would be beneficial?	Yes
2.	Age	Does the vessel have sufficient service life remaining to warrant modification of its bow to incorporate a bulb?	Yes
3.	Operational	Are there any ship missions peculiar to the ship in question or unusual equipment in the bow region which would preclude bow form modification?	No
4.	Time-At-Sea	Does the vessel spend sufficient time-at-sea to warrant incorporation of a bulbous bow?	Yes

Using these criteria the ships were categorized as shown in Tables 2, 3 and 4. Table 4 also shows which applicable criteria precluded bulbous bow installation on the non-candidate ships. These ships would never show a favorable cost-benefit ratio and in most cases the bulb would be detrimental to the ships mission. In general the marginal ships were those that, due to the possibility of increased bulb installation costs, would only show a favorable cost benefit if fuel prices were to rise greatly or, in some cases, if the ship service life was extended. The marginal ship classes would have had cost-benefit analyses performed if the analyses on all the candidate ships had shown cost payback periods of less than 3-4 years. Such was not the case.

Following a further review of these ships listed in Table 2, it was determined that some ship classes could immediately be removed from consideration. These ships were as follows:

AE 32. These ships are already equipped with large, reasonably efficient bow bulbs; there is no need to consider a new bulb design.

AOR 1. A reasonable bulb hydrodynamic design for this ship already exists; however model tests already performed indicated that this bulb would increase the resistance throughout the practical range of speeds. Additional model testing would be required to determine if, using current technology, a bulb design giving improved performance could now be developed for the AOR 1 hull form.

T-AKR 9.[1] Ship in reduced operational status.

T-AOT 168 & T-AOT 181. Ships of these classes are chartered by the Military Sealift Command (MSC). As negotiations between the Navy and the owners would be required, the additional cost involved lead to the removal of these ships from consideration.

1. Subsequent to this study the T-AKR 9 has been placed back on active duty. Accordingly it is recommended that this ship be included in any futher cost/benefit analysis.

Table 2. List of Candidate Ships for Bulbous Bow Retrofit

The following ships have a significant probability of benefitting from a bulbous bow retrofit:

Classification/ Hull Number	Name	No. of Ships in Class	Remarks
AE 26	KILAUEA	4	AE 32 Class is AE 26 Class fitted with larger bulb. AE 26 Class prime backfit candidate.
AE 32	FLINT	4	
AFS 1	MARS	7	
AGF 3	LASALLE	1	AGF 3 is the same .. 1 as LPD 1 Class
T-AKR 9	METEOR	1	
AOR 1	WICHITA	7	
T-AOT 168	SEALIFT PACIFIC	9	
T-AOT 181	POTOMAC	1	
LCC 19	BLUE RIDGE	2	
LHA 1	TARAWA	5	
LKA 113	CHARLESTON	5	
LPD 1	RALEIGH	2	
LPD 4	AUSTIN	12	
LPH 2	IWO JIMA	7	
LSD 36	ANCHORAGE	5	
------	ADM. WM. M. CALLAGHAN	1	

Table 3. List of Marginal Ships for Bulbous Bow Retrofit

The following ship have a low probability of benefitting from a bulbous bow retrofit:

Classification/ Hull Number	Name	No. of Ships In Class
AE 21	SURIBACHI	5
T-AGS 26	SILAS BENT	4
T-AGS 29	CHAUVENET	2
T-AGS 38	H. H. HESS	1
AO 143	NEOSHO	6
AOE 1	SACRAMENTO	4
T-AOT 165	AMERICAN EXPLORER	1
T-AOT 182	COLUMBIA	4
ASR 21	PIGEON	2
T-ATF 166	POWHATAN	7
ATS 1	EDENTON	3
LSD 28	THOMASTON	8

Table 4. List of Non-Candidate Ships for Bulbous Bow Retrofit

The following ships fail to meet the indicated bulb retrofit criteria from enclosure (1) and are therefore considered non-candidates:

Classification/ Hull Number	Name	No. of ships in Class	Fails to meet Criteria from page 3: 1	2	3	4
AD 14	DIXIE	5		X		X
AD 24	KLONDIKE	2		X		X
AD 37	SAMUEL GOMPERS	6				X
AG 153	COMPASS ISLAND	1		X		
AO 51	ASHTABULA	3	X	X		
T-AG 164	KINGSPORT	1		X		
T-AGM 9	GENERAL H. H. ARNOLD	2	X	X		
T-AGM 19	VANGUARD	2	X	X		
T-AGS 21	BOWDITCH	2	X	X		
T-AK 271	MIRFAK	1		X	X	
T-AK 240	PVT. JOHN R. TOWLE	1		X		
T-AK 255	PVT. LEONARD C. BROSTROM	1		X		
T-AKR 7	COMET	1		X		
T-AO 57	MARIUS	2		X		
T-AO 105	MISPILLION	5		X		
T-AOT 149	MAUMEE	3		X		
AOG 77	RINCON	3		X		

Table 4. Continued

Classification/ Hull Number	Name	No. of ships in Class	Fails to meet Criteria from page 3: 1	2	3	4
AR 5	VULCAN	4		X		X
T-ARC 2	NEPTUNE	2		X	X	
T-ARC 3	AEOLUS	1		X	X	
ARS 8	ESCAPE	3		X		
ARS 38	BOLSTER	6		X		
AS 11	FULTON	6		X		X
AS 19	PROTEUS	1		X		X
AS 31	HUNLEY	2				X
AS 33	SIMON LAKE	1				X
AS 36	L. Y. SPEAR	5				X
ASR 9	FLORIKAN	4		X		
ATF 76	UTE	6		X		
LST 1179	NEWPORT	20			X	

The remaining candidate ship classes could be further divided into categories as shown by Table 5.

TABLE 5.

Auxiliary or Cargo-Ship Type Hull Forms	"Wet-Well"-Ship Type Hull Forms
AE 26	AGF 3
AFS 1	LHA 1
LCC 19	LPD 1
LKA 113	LPD 4
LPH 2	LSD 36

For the ships remaining a cost-benefit analysis is required to determine the feasibility of a bulbous bow retrofit.

COST-BENEFIT ANALYSIS-PROCEDURE

The primary motive for a bulbous bow retrofit is the potential for fuel savings. While the bulb's effect on other hydrodynamic performance concerns such as maneuvering and seakeeping must be addressed, review of previous ship designs with bulbous bows suggest that their effects are not of enough significance in themselves to affect a decision to retrofit a bulb. Hence, fuel conservation versus bulb fabrication and installation costs becomes the basis for deciding on a retrofit.

In order to carry out the bow bulb retrofit benefit/cost study, a standardized procedure was developed in Reference (2) and shown for candidate ships (see Tables 6-12); this procedure can be summarized as follows:

- Calm water speed versus power data was assembled for the various ships. In addition, estimates of the effects of a moderately-sized, non-complex (i.e., suitable for retrofit) bow bulb on the calm water powering performance of each ship were developed.

- Speed-time distributions were assembled, and estimates of the annual underway time and percent times at full load and at ballast drafts were developed, in order to synthesize an approximate "mission" for each ship.

- Fuel consumption versus horsepower data were developed for each ship.

- Using the above-described data, annual fuel consumption estimates were developed for each ship in its current "no-bulb" configuration and with a bow bulb. The differences in the fuel consumption estimates represented, for each ship, the estimated annual fuel consumption savings due to retrofit of a bow bulb.

- Preliminary lines drawings, structural sketches, and weight estimates were developed for representative retrofit-type bow bulbs.

- An estimate of the cost of fabricating and installing a representative retrofit-type bow bulb was developed.

- The estimated fuel consumption savings due to installation of a retrofit-type bow bulb were compared with the estimated costs of fabricating and installing such a bulb.

Assuming that the average price for fuel is $80 per barrel, the estimated annual savings in fuel cost has been calculated from the data in Table 11 and is shown for candidate ships in Table 12. It can then clearly be seen that the projected average savings will range from $46,000 to $231,000 annually.

One must note that all figures quoted in this report are based upon currently available information concerning speed/time profiles, hours underway per year as well as current fuel prices. Therefore a change in any one of these variables obviously could alter the timeframe required to recover initial capital investments and hence, the feasibility of retrofitting a bulbous bow on a particular ship.

TABLE 6. Principal Hull Form Characteristics of Candidate Ships for Bow Bulb Retrofit

	AE 26	AFS 1	AGF 3	LCC 19	LHA 1	LKA 113	LPD 1	LPD 4	LPH 2	LSD 36
LPP (Feet)	540.0	530.0	500.0	580.0	778.0	550.0	500.0	548.2	556.0	540.0
B_X (Feet)	81.0	79.0	82.0	82.0	106.0	82.0	82.0	82.1	84.0	82.0
T_X (Feet)	28.0	25.75	17.75	26.00	26.00	27.50	17.75	22.00	26.50	17.75
C_X	0.994	0.928	0.938	0.904	0.959	0.950	0.938	0.950	0.914	0.933
C_P	0.618	0.610	0.577	0.579	0.665	0.610	0.577	0.632	0.567	0.603
Full Load Displ(tons)	20,600	17,500	10,790	18,500	39,290	19,230	10,790	17,000	18,080	16,150
Ballast (tons)	18,500	12,850	------	------	------	12,131	------	------	------	------

Table 7. Representative, Peacetime Speed/Time Distributions for U.S. Navy Auxiliary and Amphibious Warfare Ships

Auxiliary Replenishment-Type Ships (1)

Speed Range (knots)	percent Time
0-10	16
10-12	19
12-14	17
14-16	19
16-18	14
18-20	10
20-22	5

Amphibious Warfare-Type Ships (2)

Speed Range (knots)	Percent Time	
	CONUS Deployment (3)	Extended Deployment (4)
0-5	21	10
5-10	44	23
10-15.5	9	25
15.5-21	21	37
21-Max	5	5

(1) Excludes AGF 3. This speed/time distribution is the peacetime speed/time distribution used by NAVSEA for recent feasibility studies of AFS, AOE, and AOR-type ships.

(2) Includes AGF 3. This speed/time distribution is the peacetime speed/time distribution used in the development of the LSD 41 and LHD 1 designs.

(3) Ship based at a port in the Continental United States (CONUS).

(4) Ship based at an overseas port.

Table 8. Speed/Time and Displacement/Time Distributions Used in Fuel Consumption Computations

Candidate Ship	Speed/Time Distribution (1)	Percent Time (2) at: Full Load Condition	Ballast Condition
AE 26	Auxiliary	70	30
AFS 1	Auxiliary	70	30
AGF 3	Amphibious	100	0
LCC 19	Amphibious	100	0
LHA 1	Amphibious	100	0
LKA 113	Amphibious	70	30
LPD 1	Amphibious	100	0
LPD 4	Amphibious	100	0
LPH 2	Amphibious	100	0
LSD 36	Amphibious	100	0

(1) Distributions used in this study are quantified in Table 6. Note that the "Auxiliary" distribution is applicable to replenishment-type naval auxiliaries which steam from the base to an operating area, and then operate "on station" (i.e., this distribution is not applicable to "point-to-point" operation such as those carried out by MSC tankers and cargo ships; as noted in the text, the "Amphibious" distribution was considered to be the best available for application to future uses of these ships since it was recently developed for use in the LSD 41 design studies and is being used in the LHD 1 design studies.

(2) Amphibious warfare-type ships do not normally operate at drafts which vary greatly from the full load draft; therefore, it seemed reasonable to carry out the bulb fuel savings computations assuming constant ship displacements. This assumption probably leads to optimistic estimates of bulb fuel savings since the resistance reductions due to incorporation of a bulb would undoubtedly be smaller at reduced draft than at full load draft. The 70%/30%, full-load/ballast "split' for auxiliary replenishment-type ships was estimated; if the "split" is closer to 60/40 or 50/50, the fuel savings would be somewhat smaller than those indicated in this paper.

Table 9. Underway Hours Per Year Used in Fuel Consumption Computations

Candidate Ship	Average Underway Hours Per Year, Per Ship[1]	
	Atlantic Fleet	Pacific Fleet
AE 26	2,432	3,351
AFS 1	2,324	2,872
AGF 3	1,664[2]	--
LCC 19	2,037	2,434
LHA 1	2,495	2,596
LKA 113	2,380	1,758
LPD 1	1,943	1,990
LPD 4	2,411	2,040
LPH 2	2,193	1,837
LSD 36	1,289	1,253

(1) Date taken from Reference 7, adjusted for 12-month/year utilization of the ships.

(2) Deployed as Middle-Eastern Fleet flagship.

TABLE 10. Peacetime Annual Fuel Consumption and Estimated Annual Fuel Savings Due to Retrofit Bulb for Candidate Ships

Ship Class	Applicable Speed/Time Distribution(1)	Fleet: Atlantic	Fleet: Pacific	Estimated Annual Fuel Savings Factor(2)	Average Annual Underway Fuel Consumption(3) (bbl/yr/ship)	Average Annual Underway Fuel Savings(4) (bbl/yr/ship)
AE 26	Auxiliary/Replenishment	X		0.0112	50,039	560
			X	0.0112	68,945	772
AFS 1	Auxiliary/Replenishment	X		0.0195	37,900	739
			X	0.0195	49,676	969
AGF 3	Amphibious/Extended Deployment	X		0.0366	35,461	1,298
LCC 19	Amphibious/CONUS	X		0.0206	44,617	919
			X	0.0206	57,481	1,184
	Amphibious/Extended Deployment	X		0.0265	44,617	1,182
			X	0.0265	57,481	1,523
LHA 1	Amphibious/CONUS	X		0.0230	143,639	3,304
			X	0.0230	125,774	2,893
	Amphibious/Extended Deployment	X		0.0284	143,693	4,079
			X	0.0284	125,774	3,572
LKA 113	Amphibious/CONUS	X		0.0	26,043	0
			X	0.0	30,559	0
	Amphibious/Extended Deployment	X		0.0189	26,043	492
			X	0.0189	30,559	578
LPD 1	Amphibious/CONUS	X		0.0287	42,025	1,206
			X	0.0287	45,422	1,304
	Amphibious/Extended Deployment	X		0.0366	42,025	1,538
			X	0.0366	45,422	1,662

TABLE 10. Continued

Ship Class	Applicable Speed/Time Distribution (1)	Fleet: Atlantic	Fleet: Pacific	Estimated Annual Fuel Savings Factor (2)	Average Annual Underway Fuel Consumption (3) (bbl/yr/ship)	Average Annual Underway Fuel Savings (4) (bbl/yr/ship)
LPD 4 (5)	Amphibious/CONUS	X		0.0295	55,233	1,629
			X	0.0295	47,182	1,392
	Amphibious/Extended Deployment	X		0.0361	55,233	1,994
			X	0.0361	47,182	1,703
LPH 2	Amphibious/CONUS	X		0.0242	45,249	1,095
			X	0.0242	36,947	894
	Amphibious/Extended Deployment	X		0.0301	45,249	1,362
			X	0.0301	36,947	1,112
LSD 36	Amphibious/CONUS	X		0.0269	29,315	789
			X	0.0269	27,135	730
	Amphibious/Extended Deployment	X		0.0336	29,315	985
			X	0.0336	27,135	912

(1) See Table 6.

(2) [(Computed annual fuel consumption, ship as built) minus (computed annual fuel consumption, ship w/retrofit bulb)]/(computed annual fuel consumption, ship as built). Fuel consumption computations were carried out as explained in Reference 7.

(3) Average, for ships of this class in a given fleet, of actual fuel consumption, per Reference 7; adjusted for 12 month/year utilization of the ships.

(4) [Fuel savings factor, per (2)] x [annual underway fuel consumption, per (3)].

(5) Based on average of results of model tests for LPD 4 (with and without bulb) and LSD 41 (with and without bulb).

Table 11. Bow Bulb Retrofit Benefit/Cost Comparison

Ship/Class	Estimated Range of Annual Fuel Cost Savings(1) ($1000)	Estimated Retrofit Costs(2) ($1000)	Years to Achieve Return on Investment	Retrofit Recommendation(3)
AE 26	45-62	600	10-13	No
AFS 1	59-78	600	8-10	No
AGF 3	104	600	6	?
LCC 19	74-122	600	5-8	?
LHA 1	231-326	900	3-4	Yes
LKA 113	0-46	600	13 or more	No
LPD 1	96-113	600	5-6	?
LPD 4	111-203	600	3-5	Yes
LPH 2	72-109	600	6-8	?
LSD 36	58-79	600	8-10	?

(1) Based on an average, delivered fuel cost of $80/bbl, and on the annual underway fuel savings listed in Table 9.

(2) Excludes cost of hydrodynamic model testing of retrofit bow bulbs with their respective hull forms.

(3) The criterion for the recommendation to proceed with the bow bulb retrofit was that the investment would be paid back in about five years. For certain ships/classes where the payback period is estimated to be greater than five, the question mark (?) indicates that a further review of the acceptability of such a long payback period would be required.

Table 12. Average Age and Remaining Service Life, as of 1982, for Candidate Auxiliary and Amphibious Warfare Ships

Ship/Class	Average Age of Ships in Class	Total Service Life (years)	Remaining Service Life (Average) (years)
AE 26	12	30	18
AFS 1	15	30	15
AGF 3	18	30	12
LCC 19	12	30	18
LHA 1	4	30	26
LKA 113	13	30	17
LPD 1	20	30	10
LPD 4	14	30	16
LPH 2	17	30	13
LSD 36	12	30	18

However based upon the currently available information contained herein, the ships most likely to benefit from such a program are the LHA 1, LPD 4, LPD 1, AGF 3, and LCC 19 class ships (A suggested way to retrofit a hull with a bulbous bow as well as the associated costs involved will be discussed in detail later in the paper).

Two major points also fall out of this procedure (see Tables 7-11). First is that the maximum fuel savings for a bulb occur at design speed and will decrease in effectiveness as ship's speed decreases (see Table 13 and Figure 1). This is explained by the fact that at low speeds frictional resistance is the predominant portion of a ship's total resistance. Thus at slow speeds a bulb's ability to reduce wave-making resistance becomes small.

A second point is that due to their operating profile, two-draft ships (i.e., those ships that would operate part-time at a full load draft and part-time at a ballast condition draft) are not appropriate candidates for bulbous bow retrofits. This result is indicated by studies that show when bulbs are designed for a deep draft condition they will perform poorly at a ballast condition. As shown by Table 11 the annual potential fuel savings will be, at best, half that for a single-draft ship. Accordingly, from an economic standpoint the time required to recover the initial capital costs for design, construction, and maintenance is so great one cannot justify retrofitting bow bulbs on two-draft ships. Thus we have removed these ships from further cosideration.

Therefore, one may consider the amphibious warfare type ship to benefit the greatest by the retrofitting of a bulbous bow. What follows is an example of this procedure for an amphibious warfare type ship.

BULB RETROFIT PROCEDURE

To meet projected fuel savings a bulb that is to be retrofitted will require a detailed design effort. Once candidate bulbs are designed model tests will be required to verify the optimum bulb configuration and upon the

Table 13. Predicted SHP, With and Without Retrofit Bow Bulb for an Amphibious Warfare Type Ship

		Displ = 17,000 tons		
$V/(L)^{0.5}$	V_k	SHP w/o Bulb(1)	$\frac{\text{SHP w/Bulb}}{\text{SHP w/o Bulb}}$ (2)	SHP w/Bulb(3)
0.513	12	3,750	0.964	3,165
0.598	14	6,150	0.961	5,910
0.683	16	9,700	0.951	9,225
0.769	18	14,700	0.934	13,833
0.854	20	20,700	0.932	19,405
0.940	22	31,400	0.938	29,453

(1) Data from Reference 7. Note that ship LWL = 548.1 ft; ship LBP = 556 ft.

(2) See Figure 1

(3) SHP w/bulb = (SHP w/o bulb) x [(SHP w/bulb)/(SHP w/o bulb)].

confirmation of the bulb's performance the design lines drawings can then be prepared.

These designs, as shown by Figures 2-4 will be "add ons" to the existing hull structure in lieu of cutting away the existing forefoot and installing a bulbous bow replacement. This method is proposed in an effort to minimize the actual construction costs. Several advantages envisioned by this method are:

- Much of the new forefoot could be prefabricated
- Minimize the amount of hull structure affected by the retrofit
- Minimize the amount of drydocking time required

Use of the alternative scheme (i.e., cutting away part of the existing bow structure) would present several major disadvantages. Perceived problems with this method would be :

- Before finalization of the bulb design, additional drydocking would probably be necessary in order to determine or confirm the offsets in way of the hull/forefoot "cut" line and the location of the existing internal structural elements.
- Plating above and aft of the "cut" line would have to be removed (and reinstalled), and similarly, corresponding plating on the new forefoot would have to be left off (and installed later) in order to facilitate the attachment of the forefoot floors, bulkheads, frames, stringers, etc., to the corresponding structure in the main hull.
- Hull systems in addition to hull structure might be involved; for instance, ballasting, and anchoring (e.g., chain locker arrangements) systems might require modification.

Based on this alteration method a cost estimate comparable to a class F estimate was performed as shown in Table 14. Savings in this estimate could be achieved if the drawings and construction were performed at a commercial shipyard. Further savings could also be anticipated by using furnacing mockups and plate sub assemblies for fabrication of the "nose" (i.e., that part of the bulb forward of the point of maximum sectional area). Further savings for a class of ships could also be anticipated as the engineering work and drawings would only have to be done once per class.

BOW BULB DESIGN METHODOLOGY

Care must be taken in the task of selection and design of bulbous bows for ships which are considered to be appropriate candidates. Currently, due to the complexity of bulb/hull hydrodynamic interactions as well as lack of reliable theoretical assets, the contemporary bulbous bow design technique is heavily reliant on historical data; and refinement of the initial design must be based on model test experiments with specific bulb/hull combinations.

On the basis of the known available data and other information in the literature, three seperate approaches to the design of bow bulbs can be readily envisioned:

1. Bow Bulbs Design Without Use of Design Charts - In this design process designers are completely unfettered by any prescribed procedures or constraints. The designer's experience and judgement is supported by the results of many experimental investigations of bow bulbs which are documented in the literature. These findings are studied, sifted, and consolidated into a number of design-guidance statements for use in shaping bow bulbs.

The success of this approach depends largely on the designer's interpretation and use of the existing body of miscellanous and sometimes conflicting information. By following this approach, the designer has no reliable way of predicting the quantitative effect that a bulb can be expected to have on ship resistance and shaft horsepower. However, for fine-lined

Table 14. Class F(1) Type Cost Estimate for a Bulbous Bow Retrofit

Note: Costs are in FY 82 dollars and are based on having the retrofit work performed at the Philadelphia Naval Shipyard; cost estimate was performed by contractor personnel who are familiar with estimating procedures and factors used at the Philadelphia Naval Shipyard. Cost breakdown is approximate.

Basic Peliminary Drawings		
Technical Documentation		
Supplemental Drawings		
Changes to Existing Drawings		
Inspections		
Field Liaison		
Prorated Drydocking Costs		
Subtotal		$322,000
Bulb Materials (Steel plating, structural sections, etc.)		$45,000
Bulb "Nose" Fabrication Labor		
o Plate Furnacing Mockups	$43,000	
o Subassembly of "nose" Parts	$29,000	
Subtotal		$72,000
Other Bulb Fabrication Labor		
o Fabrication of Remaining Bulb Structure		
o Bulb Installation		
o Testing for Watertightness		
o Hull Fairing		
o Painting and Preservation		
o Draft Marks		
Subtotal		$482,000
Total		$921,000

(1) A Class F cost estimate utilizes a factor of 1.4 times the actual anticipated cost.

ships (having block coefficients of less than 0.60), encompassing most of the Navy auxiliary and amphibious warfare ships, some guidelines can be set forth reflecting the general consensus of the literature (Reference (3,4)). Reference (5) was an effort to provide some guidelines to assist the naval architect during the initial stages of developing a bulbous bow.

2. Bulb Design by the Use of Design Charts - More rigorous bow bulb design methods, based on historical data, were attempted by Taylor, Kracht, and several other investigators.

Among all these studies, Reference (6) may be considered as the most definitive. This paper contains quantitative information for the initial design of bow bulbs and evaluation of the associated change in horsepower. Design charts which are presented herein are based on analysis of routine test results at the Maberg & Berlin Model Basins, supplemented by results of additional tests to fill in the data. The design charts cover a wide range of hull forms with C_B's ranging from 0.56 to 0.82 at increments of 0.02, which were fitted with a variety of bow bulbs and tested over a range of Froude Numbers. One of the shortcomings of Reference (6) is that the independent variation of the different bulb parameters to derive design charts, bulb/hull interaction other then C_B (i.e., entrance angle, C_P, etc.) and the interrelations between the bulb parameters are neglected (see Appendix A). Thus it is essential that the designer's judgement be coupled with the use of the curves in the design charts. The advantage of using these design charts is that they can be used to judge the effect of bulb design variations on the required power of a bulbous bow ship and thereby serve to assist in decision making. Reference (6) attempted to use these charts to provide a near-optimum bulb design methodology (assuming that the charts were fundamentally valid). Two LHA 1 retrofit bulbs based on this methodology were designed and tested at the David Taylor Naval Ship Research and Development Center (DTNSRDC). While the results obtained were encouraging, further model testing to involve different hull forms will be required to ensure the validation of this technique.

3. Bow Bulb Design Through Numerical Techniques - Currently little research has been done in development of numerical techniques for predicting the characteristics of bulbous bows. However, one computer program that has shown promise is the XYZ Free Surface (XYZFS) program. To date this program has already been applied in calculating the wave-making resistance of hull forms with sonar domes and shows good correlation with model test results. Therefore we anticipate that if the proper method of modeling a bulbous bow can be found, XYZFS will become a valuable tool for the bulbous bow designer.

Towards this objective, research is currently underway on two LHA 1 bow bulbs. These bulbs were designed by application of the Kracht method (described earlier in this section). It is hoped that, by this analysis, a better understanding of the parameters that have thus far shown the greatest influence on the performance of bulbous bows can be achieved.

CONCLUSIONS

Through the development of a systematic cost/benefit analysis it has been shown that the retrofitting of bulbous bows will provide significant life cycle fuel savings. The procedure developed was based upon:

- Speed/power relationships for the ship in calm water both with and without bulb
- Total steaming time
- Speed/time distribution for the ship as it is deployed
- Specific fuel consumption over the range of operating speeds

Based upon currently available information it has been shown that among the ships most likely to benefit from such a program are the LHA 1, LPD 4, LPD 1, AGF 3, and LCC 19 class ships. Savings in fuel costs for these ships will be, at a minimum, $96,000 per year per ship.

It must be stressed that once the decision to retrofit a bulb is made, a series of hydrodynamic model tests should be performed to validate the predicted performance improvement of the selected bulb design. Though the use of historical data and design charts can help the designer select a candidate bulb design these procedures can only be considered an adjunct to the overall design procedure. Soon the use of numerical modeling techniques will also become a part of this process.

For the ships recommended to undergo a bulbous bow retrofit a complete ship alteration (SHIPALT) package, including detailed cost estimates must be prepared. This work is being done on the first three ship clases which show the shortest payback period. In an effort to reduce the overall costs involved it has been suggested in this paper that the retrofit be accomplished by "adding-on" to the existing hull structure rather than cutting away the existing forefoot and installing a bulbous bow replacement.

This effort has shown that through the retrofitting of selected ships with bulbous bows a viable way has been found to reduce the fuel requirements of the fleet. However, until a bulb retrofit program is implemented, the Navy will pay thousands of dollars more in fuel costs than necessary for every year that this program is delayed. Further, continued delays in initiating such a program will result in the removal of candidate ships from consideration as their remaining years of service life diminish beyond the critical payback point. Accordingly, the authors strongly encourage incorporation of a bulb retrofit program into the Navy's overall conservation energy program as soon as possible.

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APPENDIX A

Per Reference (6) it is shown that Kracht has introduced six geometric parameters for delineation of the bulb form. Using the bulb quantities depicted in Figure (A-1) these parameters can be defined as follows:

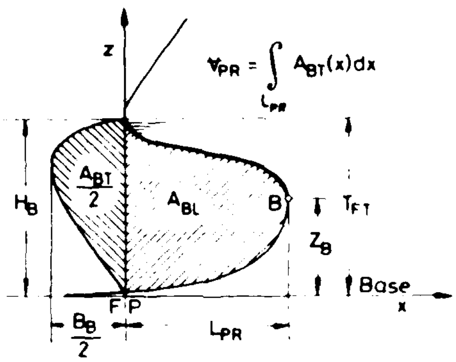

Fig. A-1

a. Breadth parameter

The maximum breadth B_B of bulb area A_{BT} at the forward perpendicular divided by the beam B_{MS} of the ship:

$$C_{BB} = B_B/B_{MS}$$

b. Length Parameter

The protruding length L_{PR} divided by the length L_{PP} of the ship:

$$C_{LPR} = L_{PR}/L_{PP}$$

c. Depth Parameter

The height Z_B of the foremost point of the bulb over the baseline divided by the draft T_{FP} at the forward perpendicular:

$$C_{ZB} = Z_B/T_{FP}$$

d. Cross-Secton Parameter

The cross-sectional area A_{BT} of the bulbous bow at the forward perpendicula divided by the midship-section area A_{MS} of the ship:

$$C_{ABT} = A_{BT}/A_{MS}$$

e. Lateral Parameter

The area A_{BL} of the protruding bulb in the longitudnal plane divided by the midship-section area A_{MS} of the ship:

$$C_{ABL} = A_{BL}/A_{MS}$$

f. Volumetric Parameter

The volume V_{PR} of the protruding part of the bulb divided by th volume of displacement V_{WL} of the ship:

$$C_{VPR} = V_{PR}/V_{WL}$$

An additional bulb parameter H_B is suggested by Reference (4), where H_B is defined as the height of the bulb at the forward perpendicular.

The selection of the height and the distance from the baseline to the bottom of the bulb are matters of judgement, the bulb height H_B is constrained by two requirements: 1) it must be large enough to enable the required cross-section area A_{BT} to be developed; and 2) the top of the bulb must be an appropriate distance below the design waterline. At the same time, marked flatness of the top of the bulb should be avoided to minimize the potential for cavitation as the ship pitches and heaves. In general, it is considered that the value of Z_B/H_B should be between 0.5 and 0.9. A tentitive value of H_B can be obtained by the following formula:

$$H_B \simeq (4A_{BT})/(\pi B_B)$$

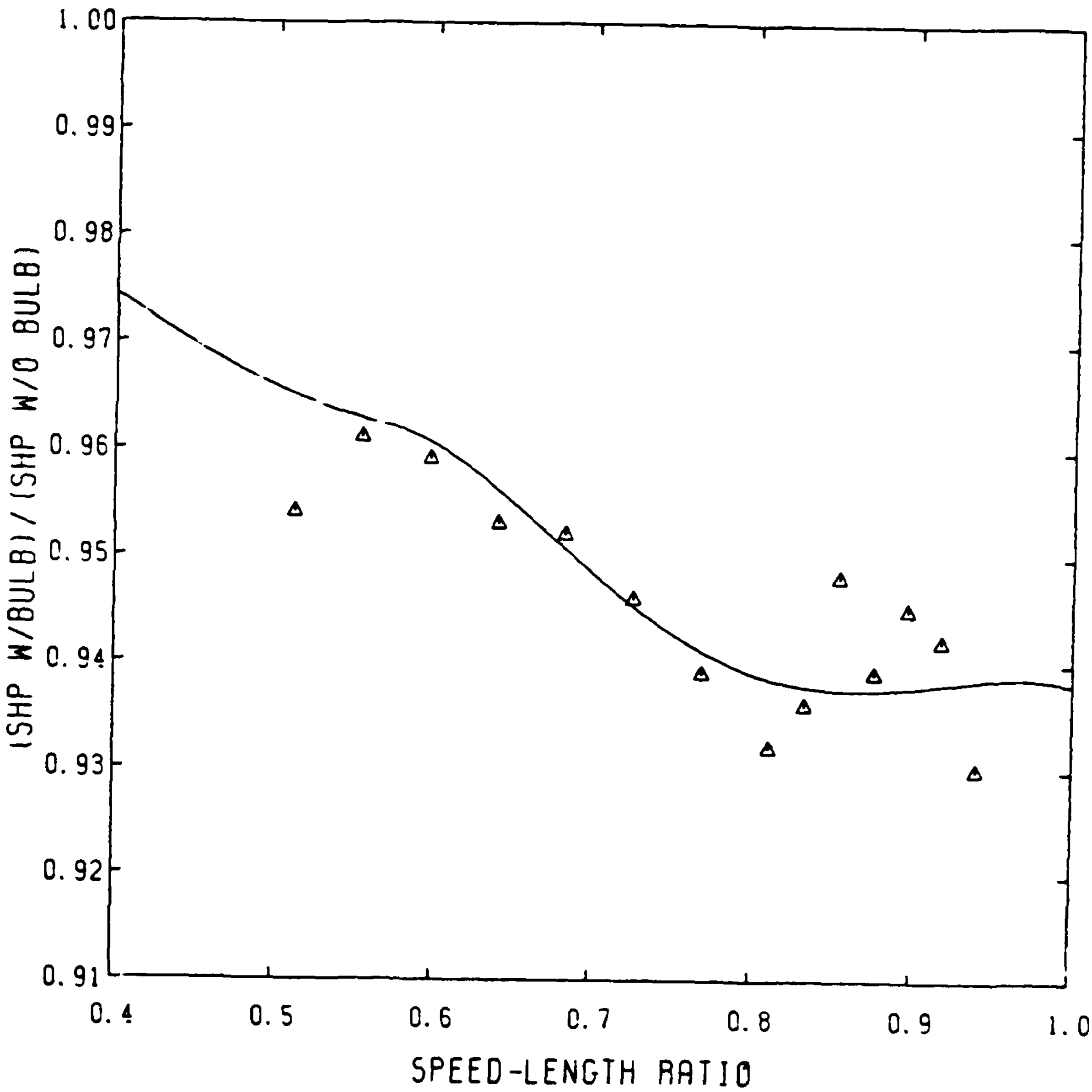

FIGURE 1. Shaft Horsepower Ratio (Bulbous Bow to Conventional Bow) for an Amphibious Warfare Type Ship Displacement=17,000 tons

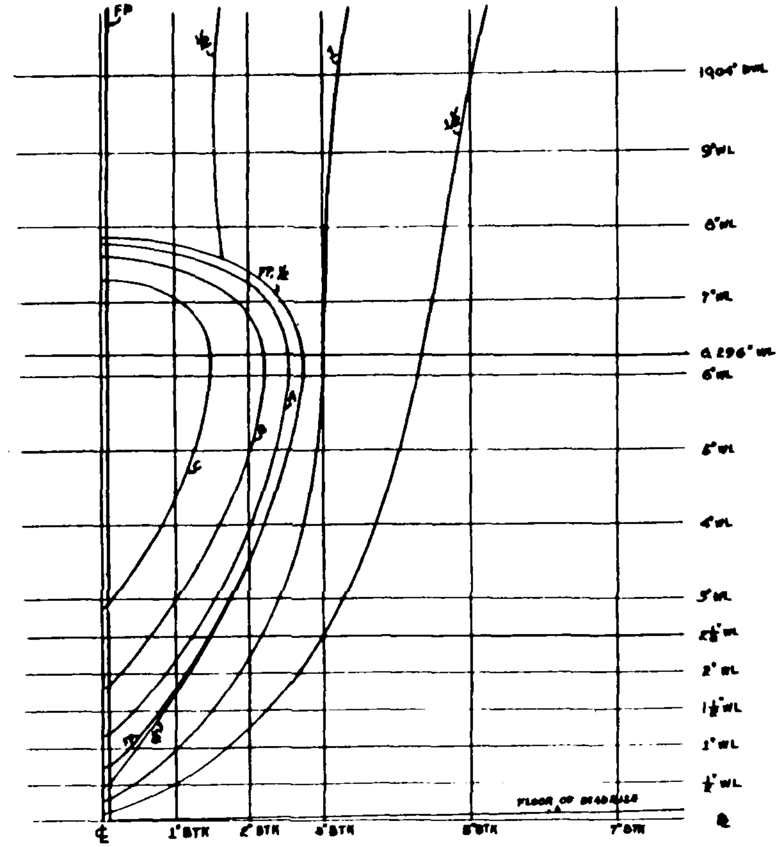

FIGURE 2. Retrofit Bow Bulb for an Amphibious Wareface Type Ship

BODY PLAN

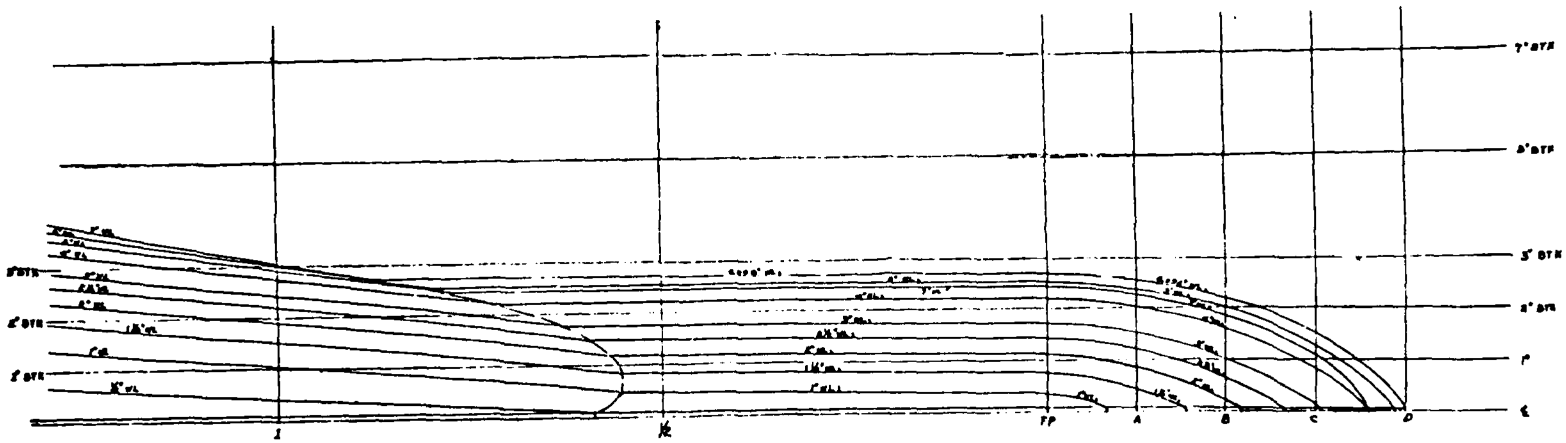

FIGURE 3. Retrofit Bow Bulb for an Amphibious Warfare Type Ship

HALF BREADTH

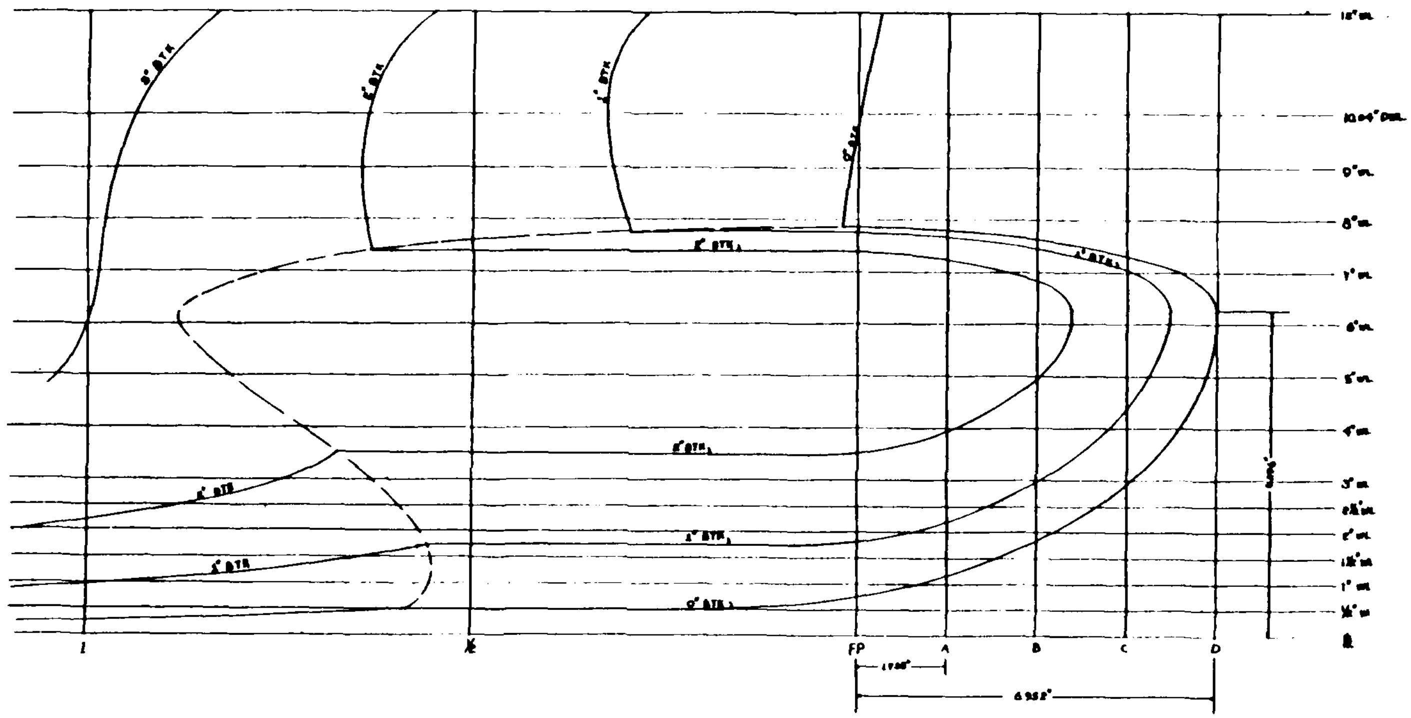

FIGURE 4. Retrofit Bow Bulb for an Amphibious Warfare Type Ship

BUTTOCK LINES

DATE
ILME